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Nb3Sn High Field Magnets
Winding in Conduit Technology
Technological Model

Technical Proposal

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Introduction

Magnet technology of Nb3Sn accelerator magnets is mostly based on the experience of superconducting NbTi magnets. Nevertheless, there are substantial differences and problems very well known in the field. Several rules can be incorporated in manufacturing process to improve Nb3Sn magnets performance:

- Smaller strands deformations during cabling;
- Magnet coils must be mechanically homogeneous structure, no one place of stress/strain concentration, including splice areas;
- Coils during reaction process should have a possibility of free longitudinal motion;
- Reacted coil transfers from-to technological fixtures is not acceptable;
- Winding cold block must be self-mechanically protected, rigid structure;
- Winding must be epoxy vacuum impregnated under the pressure;
- Winding prestress must be provided through the mechanically solid rigid elements;
- All splices must be placed outside the winding in low field areas with direct LHe cooling;
- Nb3Sn cables in areas between winding and splice should be supported by special structure providing homogeneous stress/strain distribution.

There are also several not well known issues for cables based on new superconductor technologies (MJR, PIT,…), which can cause substantial superconductor degradation, and their effect should be lowered by the design to a minimum value:
- Nb3Sn cable degradation under shearing deformation;
- New high current density cables usually more sensitive to a mechanical loads, have larger flux jumps and magnetization effects;
- Cable prestress during reaction;
- Optimal interstrand resistance;
- Degradation after the quench.

Short description of proposed winding assembly

The proposed magnet cross-section shown on Fig.1 and Fig.2. It has inner stainless steel tube, Nb3Sn coils, outer stainless steel tube and end flanges. This winding assembly used as a reaction and impregnation fixture and forms, after epoxy impregnation, mechanically rigid structure. Inner and outer tubes with end flanges work as a stainless steel conduit around the winding assembly. All winding inner space is an epoxy impregnated under a high pressure, providing needed prestress.

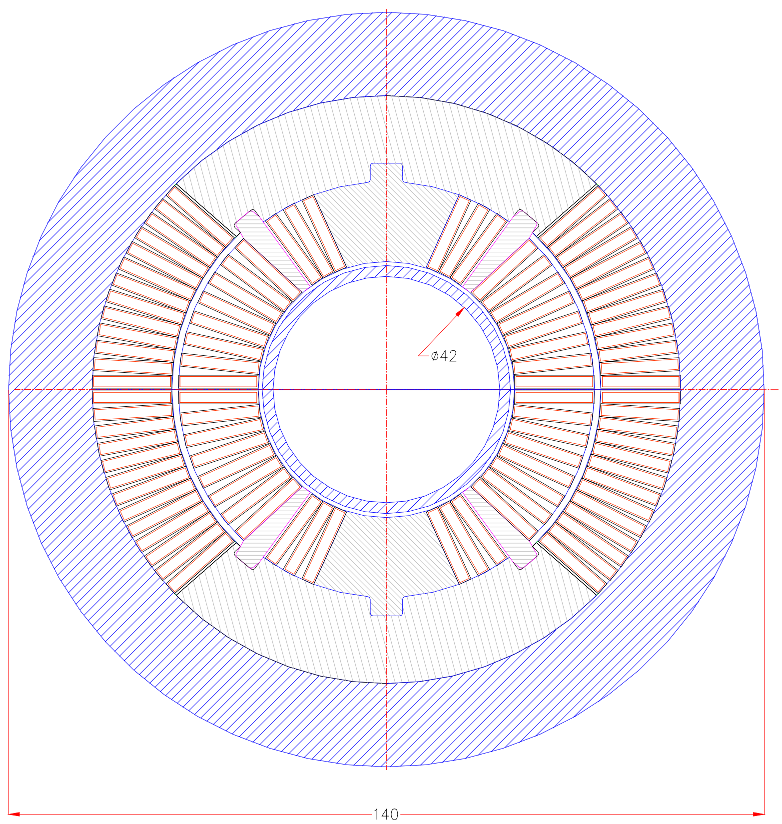

Fig.1. Magnet cold mass

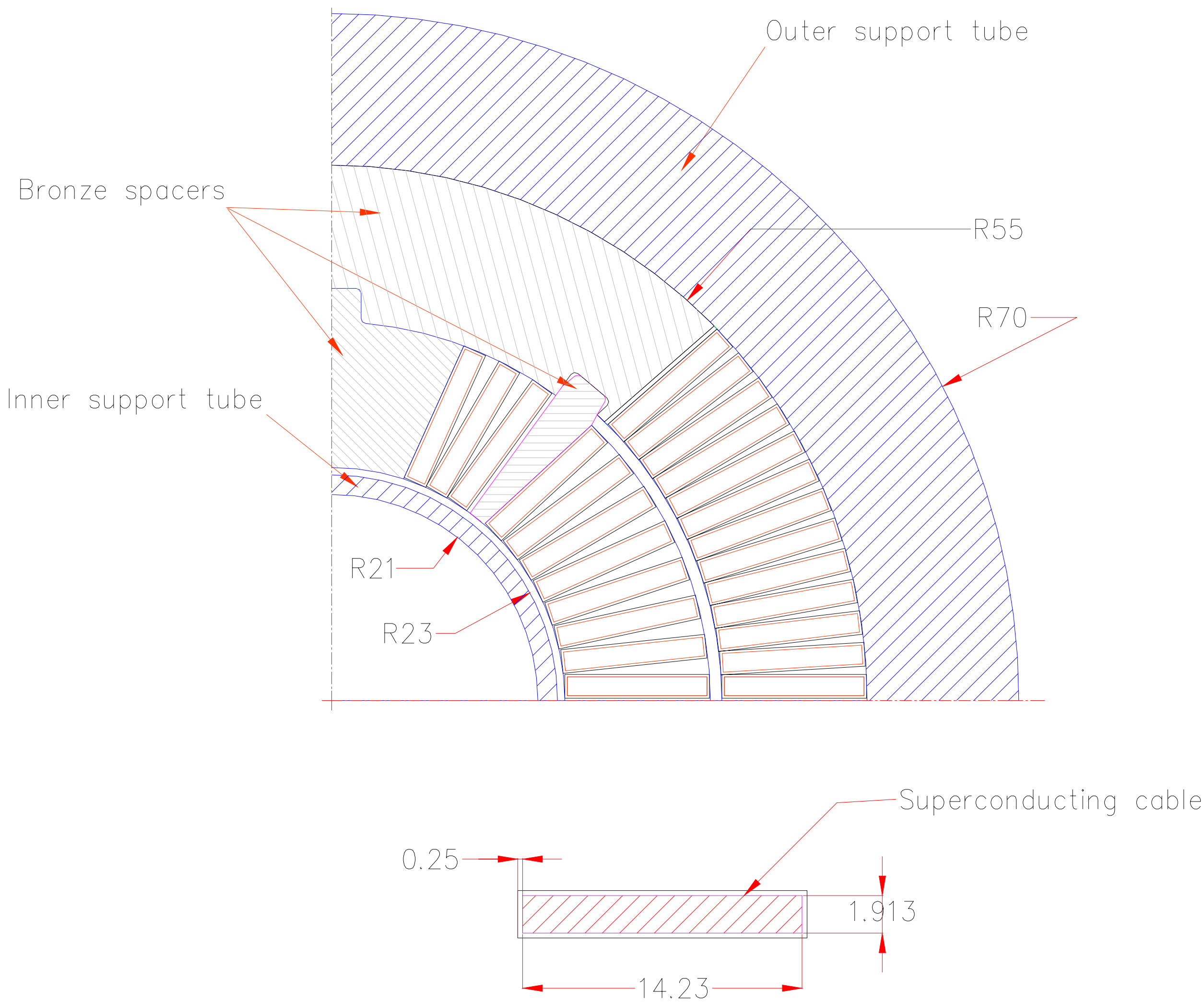

Fig.2. Magnet cross-section

Coils geometry and winding

There are two options how to wind the coil:

1. Using technique with coil mandrel, binder or ceramic tape with prepreg.
2. Inner tube is used as a mandrel.

In present design cable positioned in space with bronze wedges and bronze end spacers. Because wedges not connected with end spacers and have 5 times higher Young's modulus, there may be places of stress concentration and shearing deformation. One of the options to avoid this effect is to connect these parts with pins.

Another attractive option is to replace thick wedges by a metal tape. Several possible technical solutions with continuously distributed metal spacers can be used Fig.3. During winding process stainless steel or copper tape is used in parallel with Nb3Sn cable providing proper cable angular positioning and optimal cable prestress during reaction. This tape also increases a radial heat transfer to LHe. Additional thin spacers may improve proper cable positioning at the coil ends.

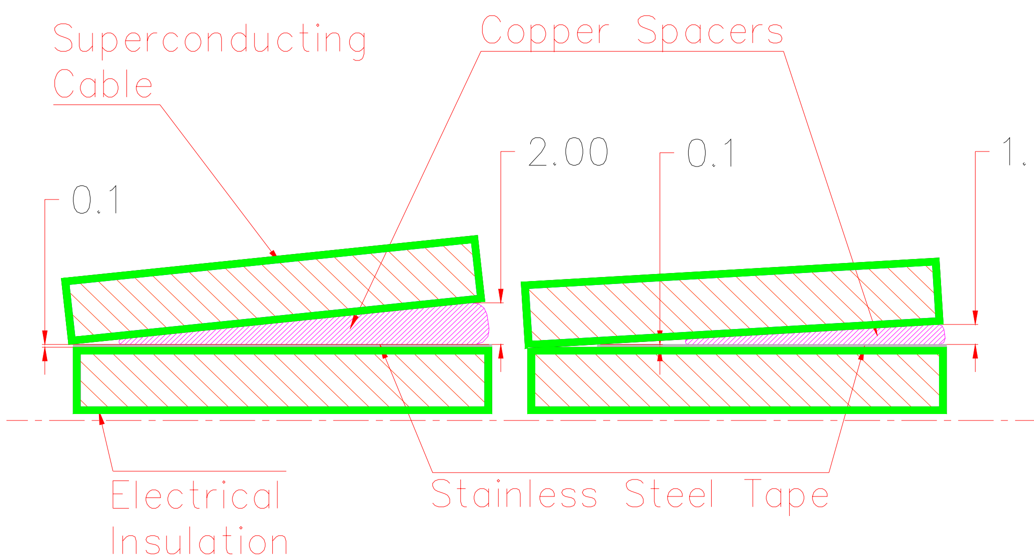

Fig.3. Distributed spacers technique

It is also possible to place the copper spacer together with superconducting cable to improve cable stability and mechanical properties. In this case only thin 0.1-0.2 mm stainless steel tape will provide additional azimuthal cable prestress during winding.

A perforated stainless steel tape wound around outer winding surface provides radial winding prestress before and during cable reaction. This tape also can be used as a quench heater.

Proposed coil structure will be mechanically more homogeneous and less sensitive to mechanical loads during assembly, cool down and operation.

Magnetic conceptual design

The main question during magnetic design was if it is possible to obtain the good field quality in aperture using the distributed spacers technique and minimum thick spacers. It was investigated several approaches and the configuration with only one shim shown on Fig. 3 looks reasonable.

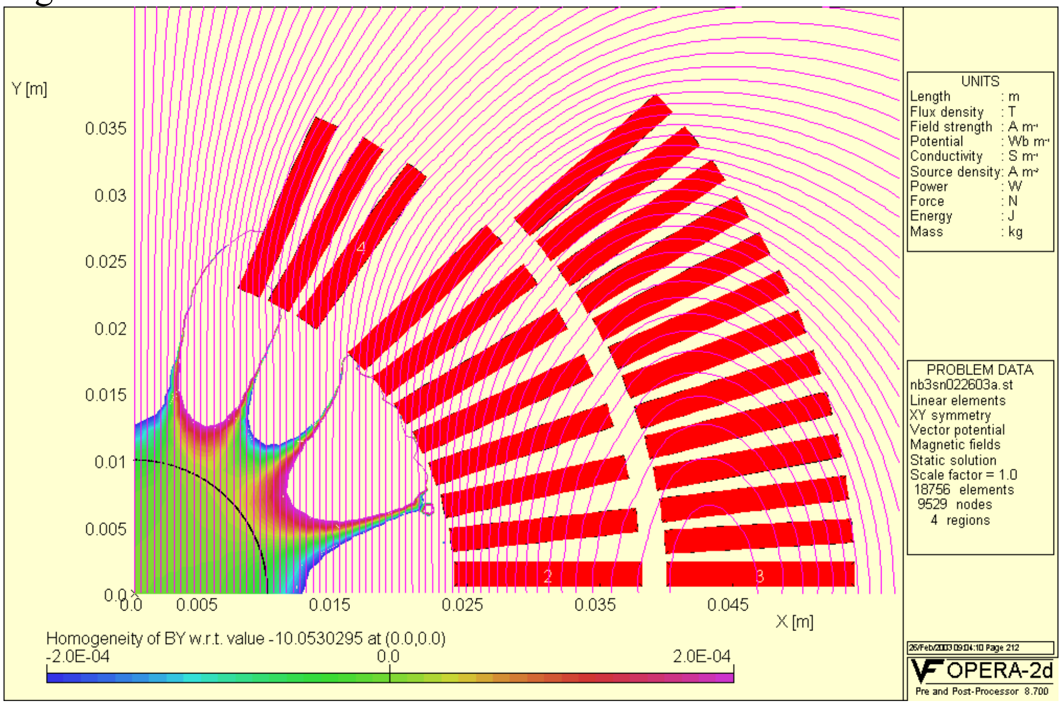

Fig. 3. Winding geometry, flux lines and field quality

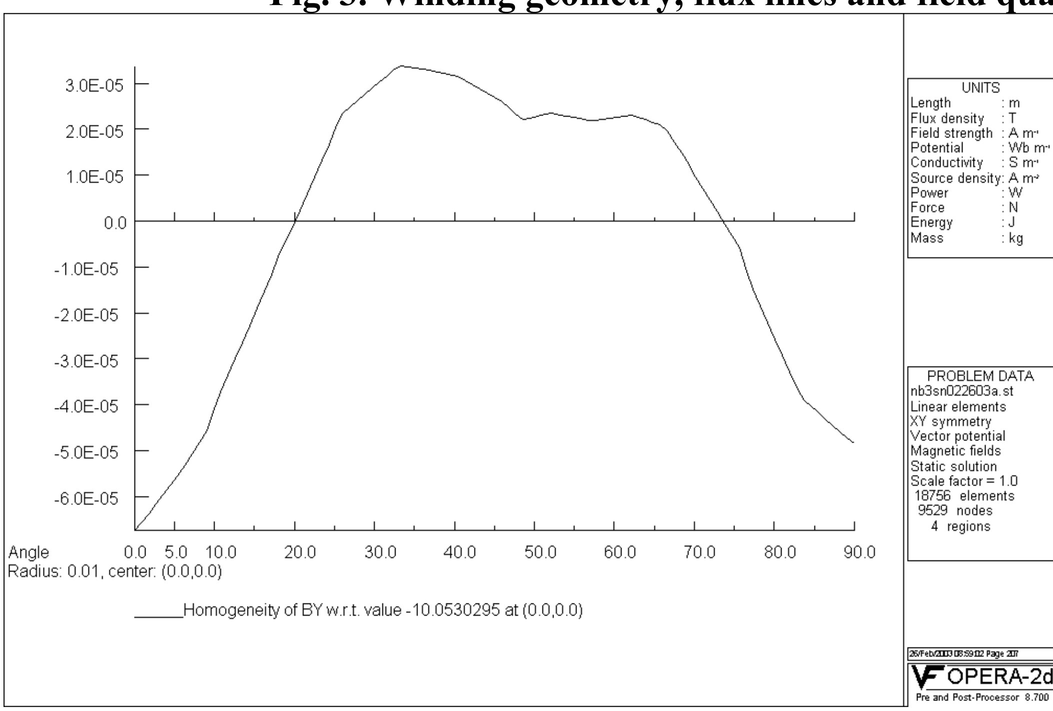

Fig. 4. By field component homogeneity at radius 1 cm

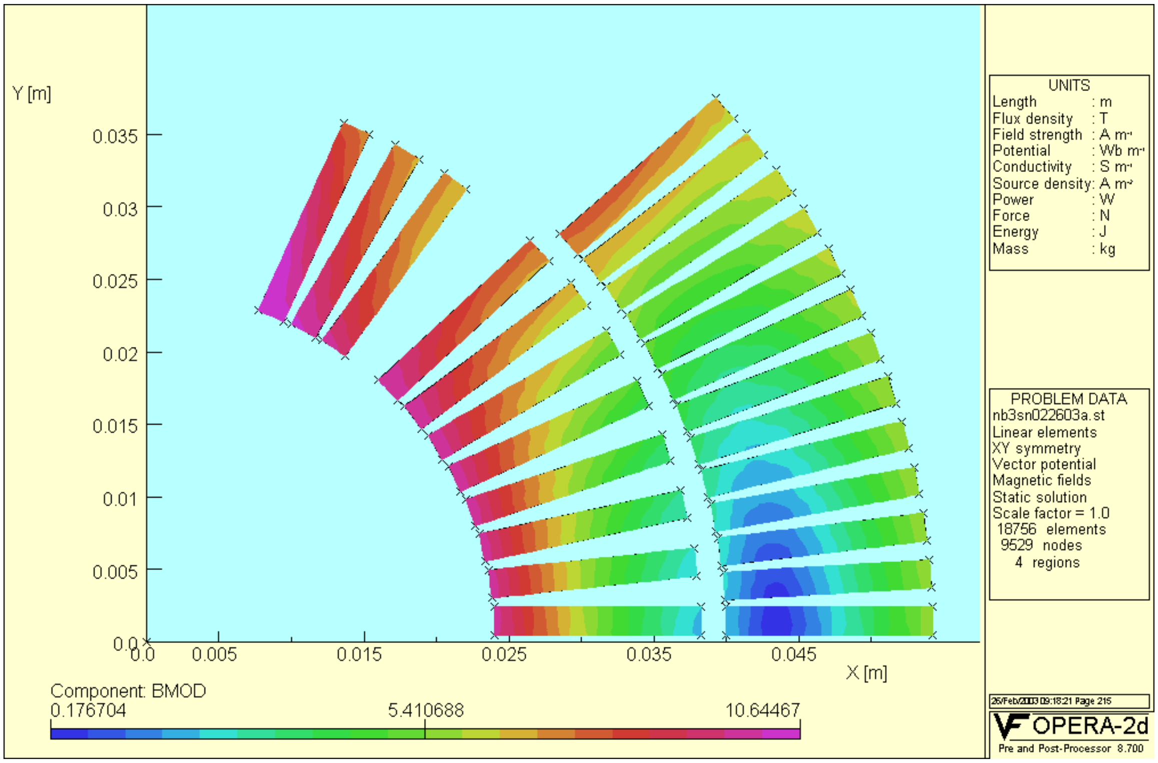

Fig. 5. Flux density distribution in the winding

Coils heat treatment (reaction)

Winding fixed on the inner tube is assembled with outer tube and end flanges forming closed volume of reaction fixture. Cable ends fixed in space with a possibility of longitudinal motion. Argon gas flow through the fixture is provided. After reaction outer tube can be removed for winding inspection and end parts gaps filling with G10 or glass tape spacers.

Splices

All splices are made outside the winding ends in a low field region and zero forces area during the winding assembly. Two NbTi cables with copper plates are soldered to the both sides of Nb3Sn cable. Splice assembly impregnated with epoxy inside the splice support fixture attached to the end flange. The splice LHe direct cooling should be provided with epoxy free areas of copper plates. After impregnation NbTi cables impregnation pipes are cutted to clean the cables for joints to current leads.

Instrumentation

The outer tube can be removed to solder voltage taps, sensors. Heaters of quench protection system also should be installed.

Winding impregnation

Inner and outer tubes with end flanges form the closed volume for vacuum impregnation. After the pumping out of the assembly, ready for use epoxy flows from an outer vessel in the inner winding volume. When the whole volume is filled in with epoxy, inlet and outlet valves/plugs should be closed. The additional epoxy pressure inside the assembly is provided by pressing a bladder type structure or by a bellow system as shown on Fig. 6. The inner tube wall thickness is trade in between a magnet aperture reduction and maximum allowed pressure. The inner tube with 2 mm wall thickness is capable to carry outer pressure no less than 60 Mpa. It is also possible to increase maximal epoxy pressure and protect inner tube from collapsing with help to an inner support rod or by providing a compensating pressure inside the inner tube.

One of the problems for superconducting windings is relatively larger than for collar structure shrinkage after cooling down. That is why winding prestress should be provided at room temperature, which protect coils from motion under Lorentz forces.

Another problem is rather high epoxy mold shrinkage during curing. It reduces the final epoxy pressure and as a result the winding prestress. Shlomo Caspi made several experiments with technological model and measured ~ 50 % prestress reduction because of this effect.

Nevertheless, it is possible to eliminate this effect if insert the thin wall tube between outer winding surface and collar, forming two separate closed volumes. One with winding, another with collar. In this case the main volume with winding is impregnated and cured as described above. The second volume is filled with epoxy later, when the first volume starts to shrink during curing. As a result the pressure from the second volume will keep permanent prestress inside the winding. The prestress drop during the second volume curing will be low because of very small epoxy volume. Besides, can be used the epoxy with filler, having zero mold shrinkage effect.

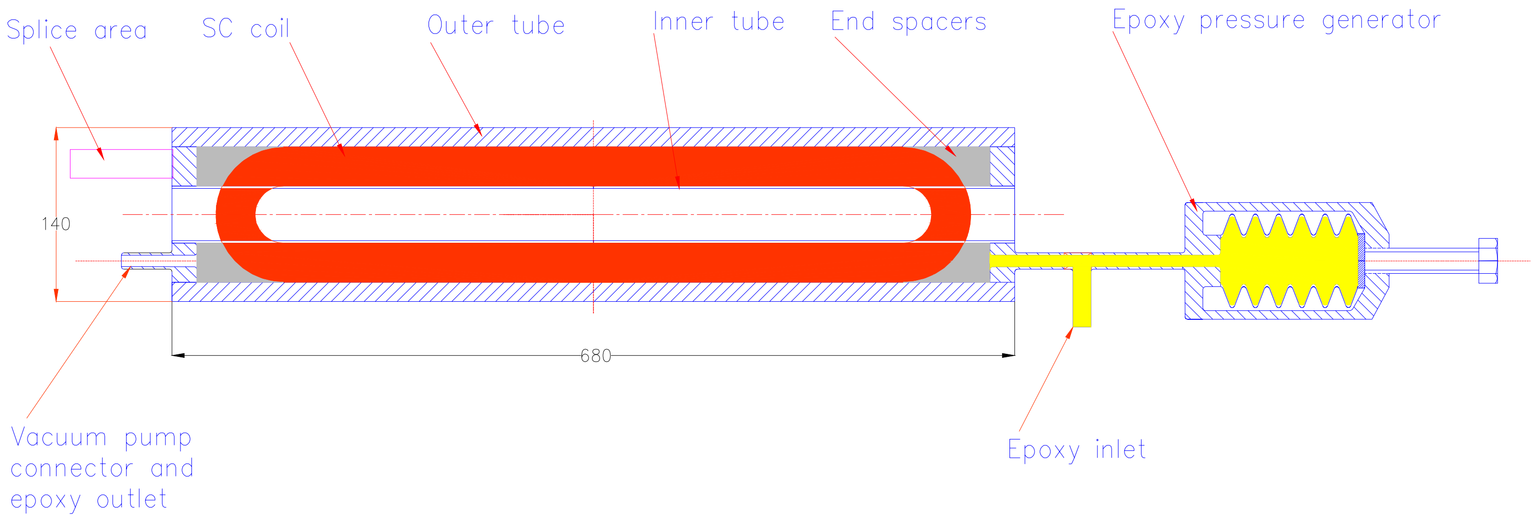

Fig. 6. Schematic view of epoxy impregnation system

Preliminary mechanical analysis

Mechanical properties of all materials supposed to be isotropic. There were used material properties as in Table 1. Results of two-dimensional mechanical analysis are shown in Appendix A Fig. 7 – 10 (vacuum impregnation) and Fig. 11 –13 (with epoxy pressure 30 Mpa).

Table 1

Material	E, GPa	μ	Thermal contraction integral, mm/m	Thermal contraction integral at 30 MPa, mm/m
Coil	44	0.3	-3.6	-3.6
Stainless steel	210	0.3	-3.0	-3.0
Insulation	14	0.3	-4.21	-2.07
Spacer	112	0.3	-3.6	-2.07

Winding assembly parameters and test

Winding assembly has the following parameters:

Inner diameter, mm	21
Outer diameter, mm	53
Length of straight section, mm	500
Cold mass, kg	80
Magnetic field in aperture, T	10.0
Maximum magnetic field in winding, T	10.7
Maximum current, kA	24
Number of layers	2
Number of turns/magnet	48
Superconducting Nb3Sn cable	
- strand diameter	1.0
- number of strands	28
- cable width, mm	15
- cable thickness, mm	2
- cable insulation, mm	0.25
Cable critical current at 12 T, kA	22
10 T, kA	30
Magnetic energy, kJ	200
Lorentz forces:	
Fx, t	206
Fy, t	176

This model does not have ferromagnetic screen that simplify the assembly and test because of reduced cold mass. Ferromagnetic yoke efficiency is rather low at fields more than 10 T. Iron saturation effects, huge cold mass and cryostat dimensions push the design of future magnets to an air core magnets with the thin ferromagnetic screen combined with the vacuum vessel or to an active superconducting shield windings.

Summary

The goal of this proposal is to initiate the activity in the design and manufacturing mechanically stable and self-protected Nb3Sn windings on the base of winding in conduit technology.

Several improvements will be addressed to this activity:

1. Improving the technological process from mechanical point of view.
   There is no one reacted coil moving or load applying.
2. Epoxy impregnation under the pressure provides winding prestress;
3. Coils with distributed spacers have low stress concentrations;
4. Inner layer spacer intercepts part of Lorentz force and provides better stress redistribution;
5. Cable with an extra copper has a better stability;
6. Rectangular cable has lower degradation;
7. Stainless steel tape provides homogeneous azimuthal prestress during winding and reaction;
8. Small number of magnet parts and tooling.

Some technical issues should be clarified during design :

1. Is it possible maintaining enough epoxy pressure to provide needed prestress before and after impregnation to eliminate outer collar structure? Or some combination of thin outer tube with outer collar will be more visible.
2. Is it better impregnate the winding with splices and NbTi current leads simultaneously or separately?
3. Is it better to wind Nb3Sn coils separately using existing technology or on the inner tube using it as a tooling?
4. Which type of epoxy pressure generator is better: bellow type, LBL bladder or large diameter pipe under transverse external pressure?
5. What type of epoxy better for impregnation under the pressure? With or without filler, low shrinkage after curing, etc.
6. Is it possible to combine copper spacer with cable applying insulation around?

The first technological model Appendix B can be manufactured and tested at the fall of this year. Manufacturing and test of mechanically stable and protected winding in conduit will move the accelerator magnet technology in right direction.

Appendix A

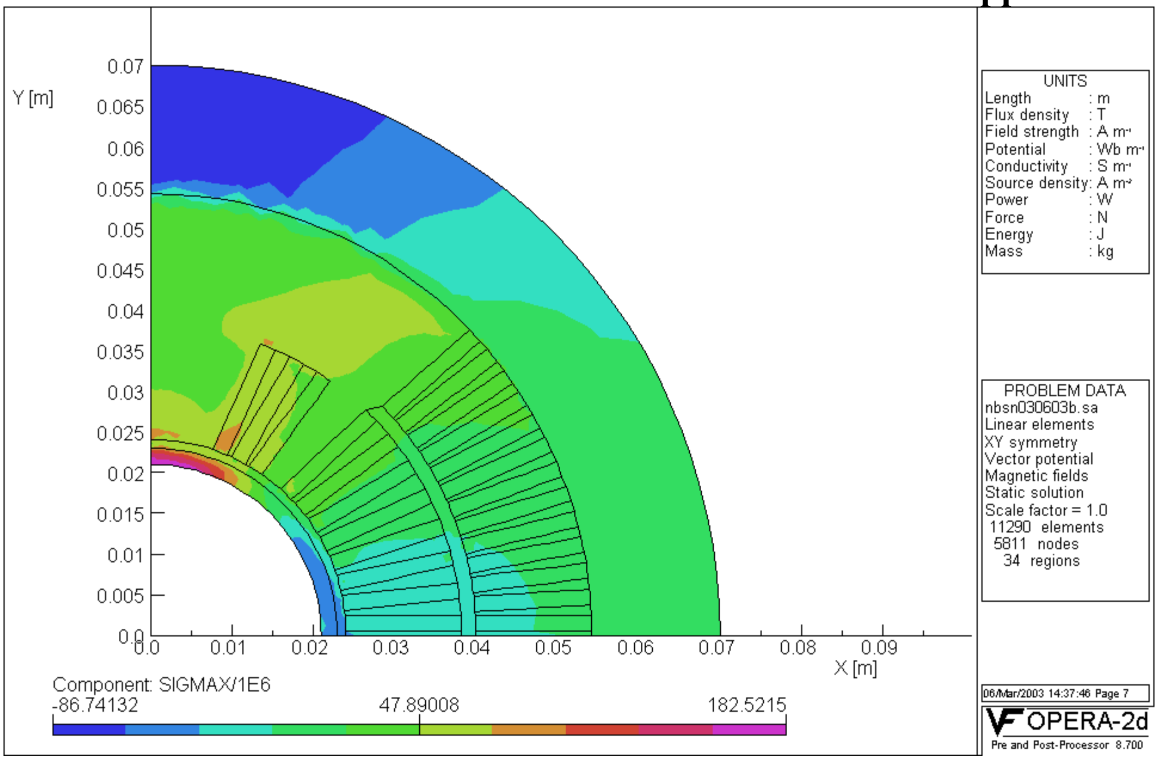

Fig. 7. Stress X component distribution in MPa at 10 T and 4.2 K

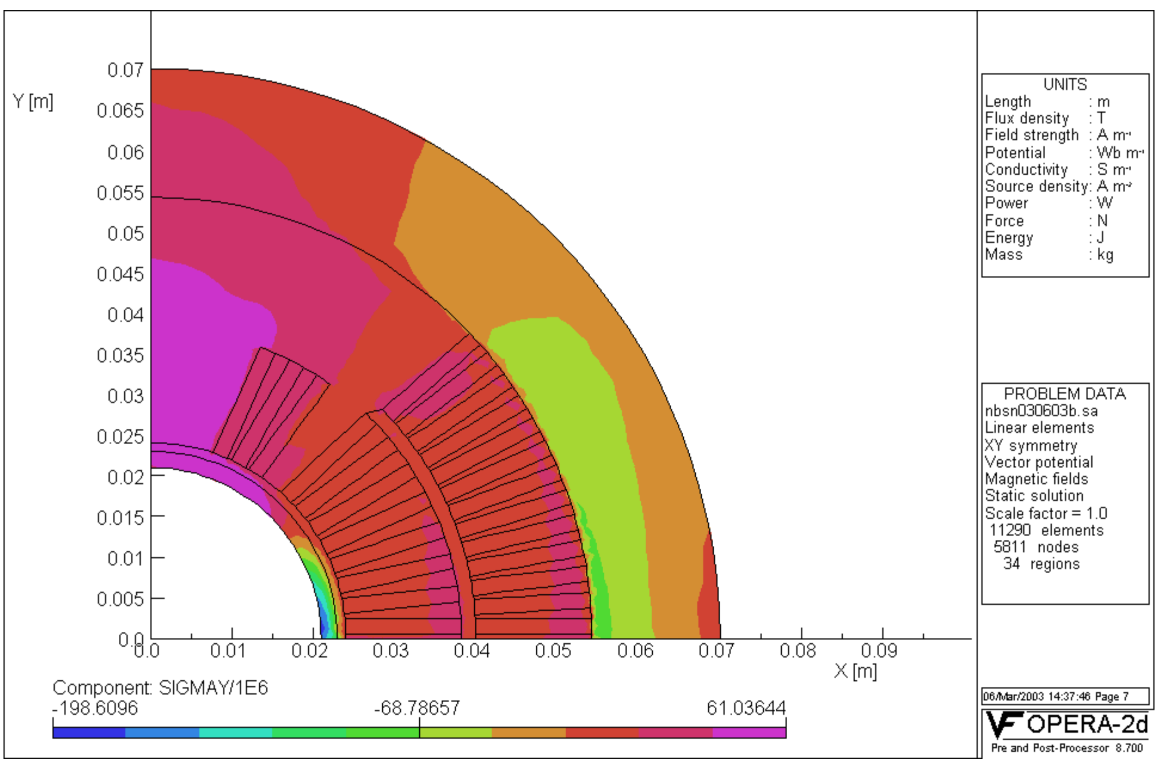

Fig. 8. Stress Y component distribution in MPa at 10 T and 4.2 K

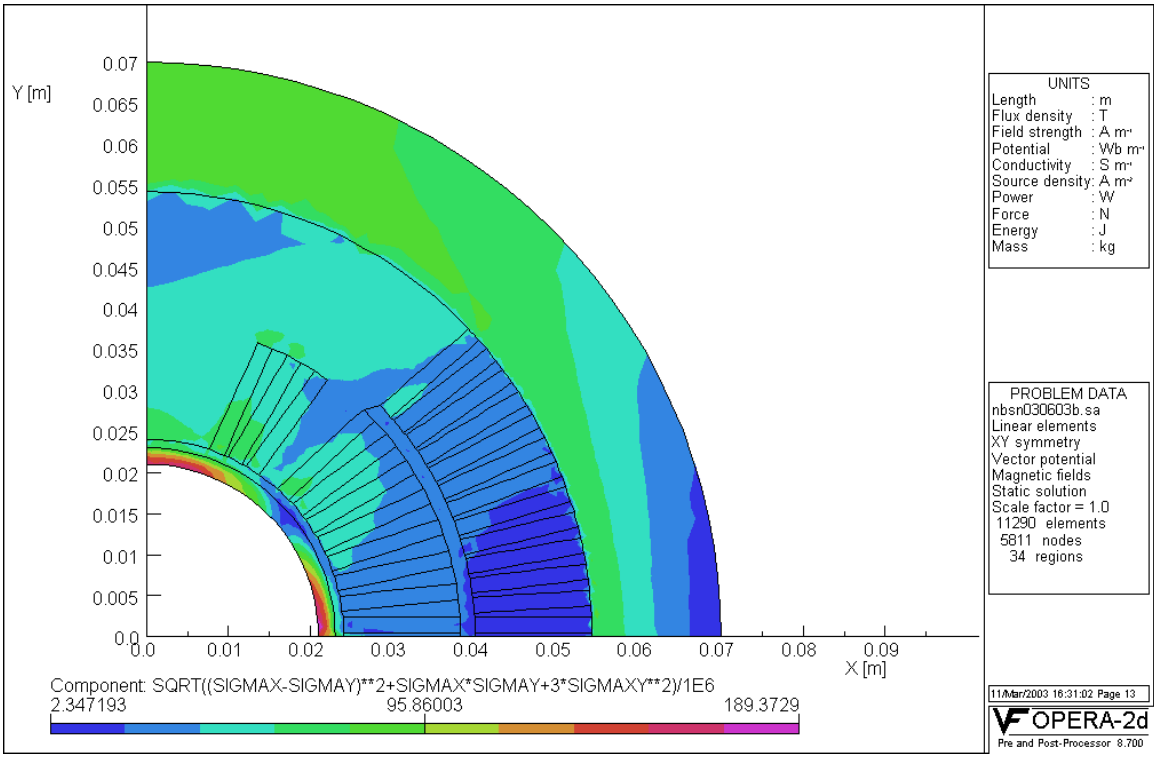

Fig. 9. Total stress distribution in MPa at 10 T and 4.2 K

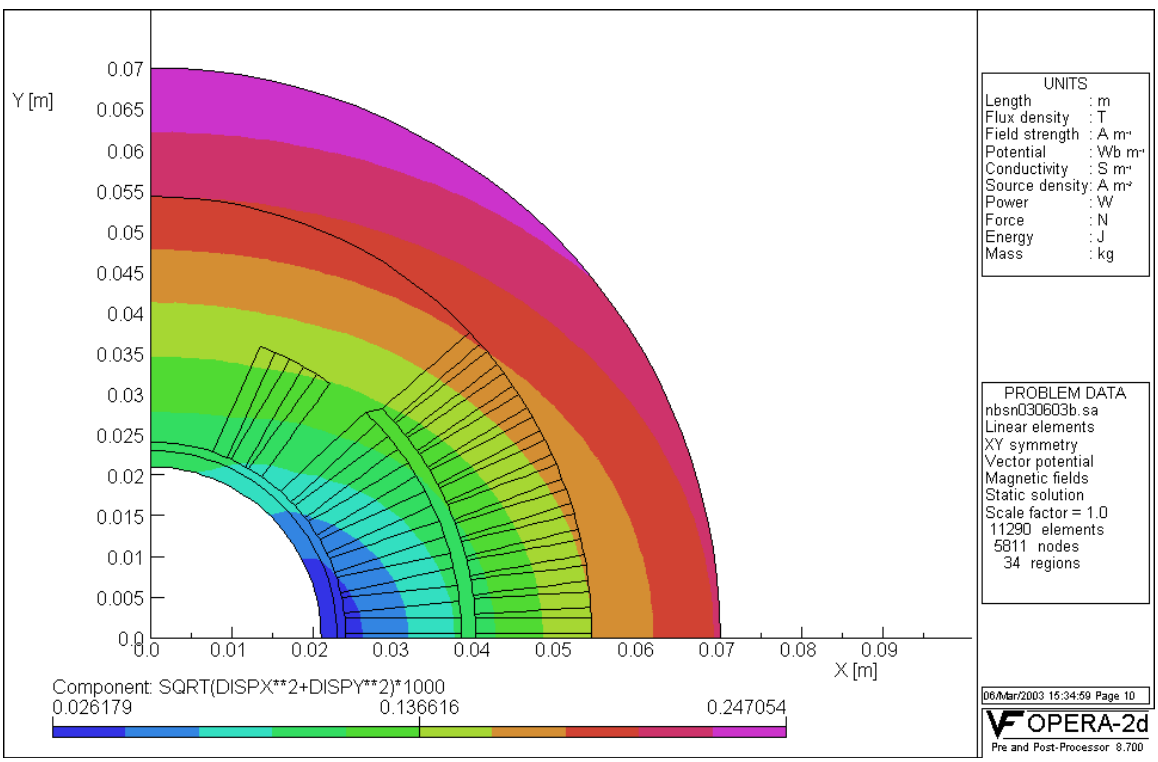

Fig. 10. Displacement distribution in mm at 10 T and 4.2 K

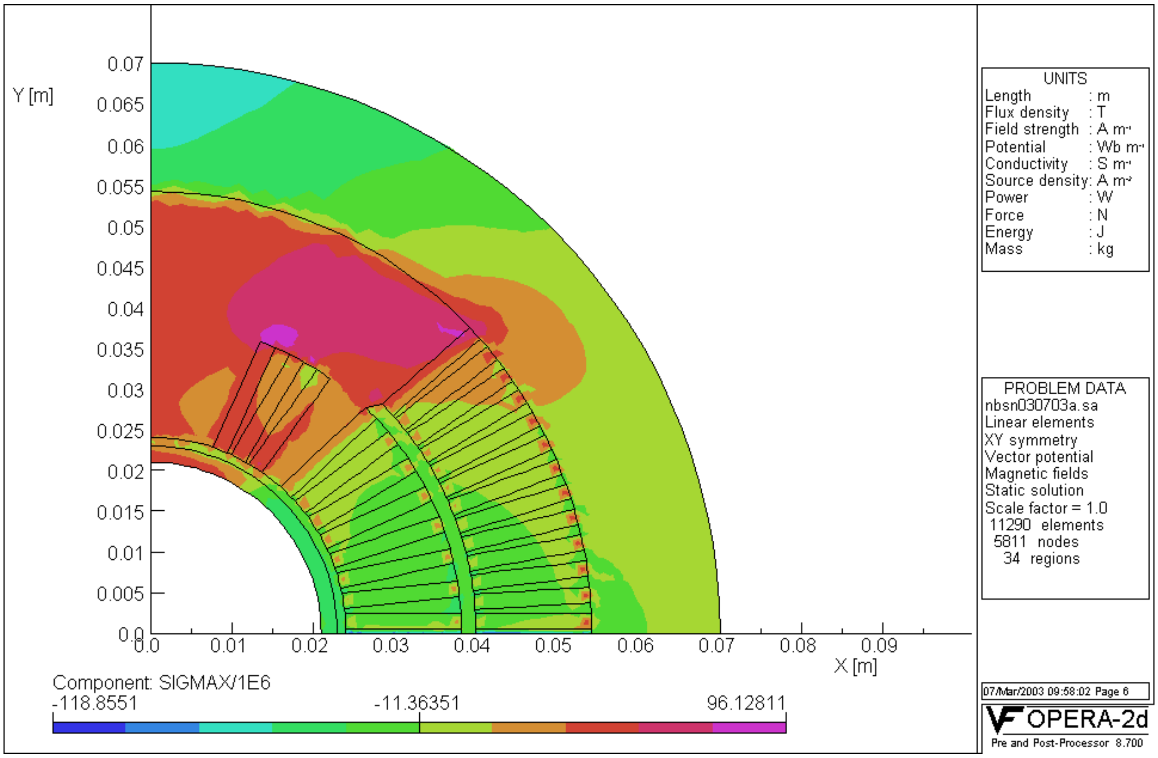

Fig. 11. Stress X component distribution in MPa at 10 T and 4.2 K

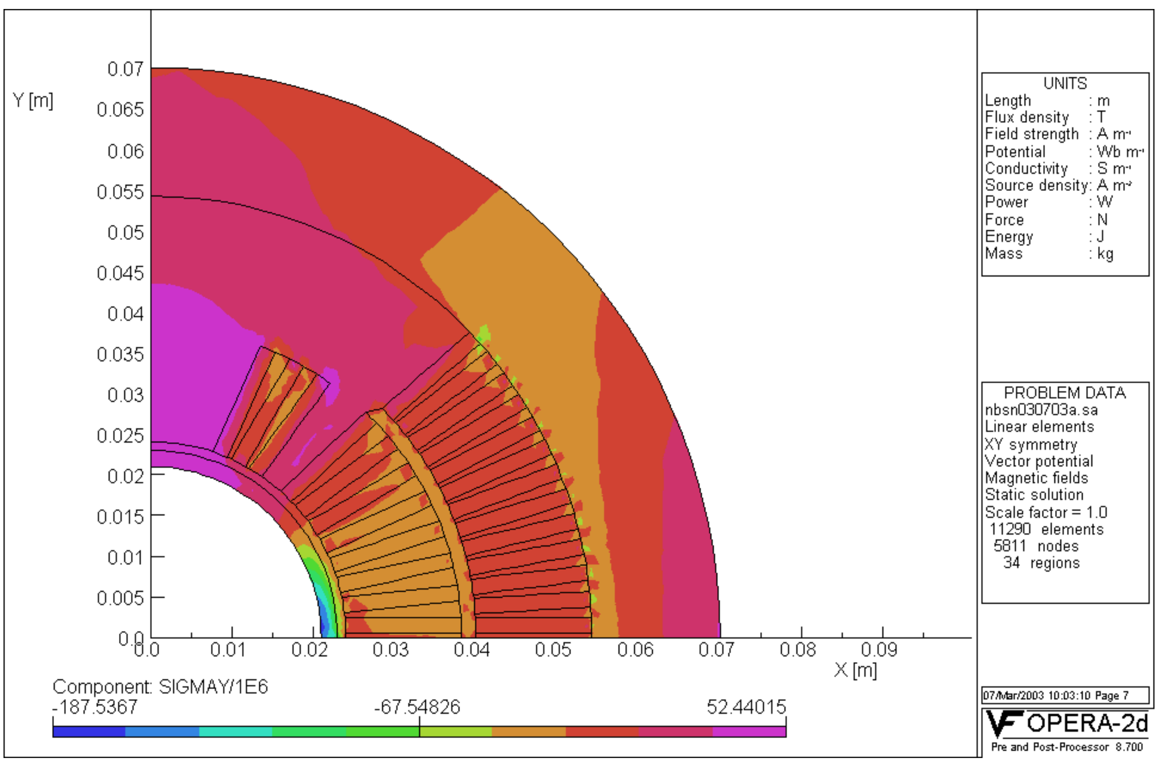

Fig. 12. Stress Y component distribution in MPa at 10 T and 4.2 K

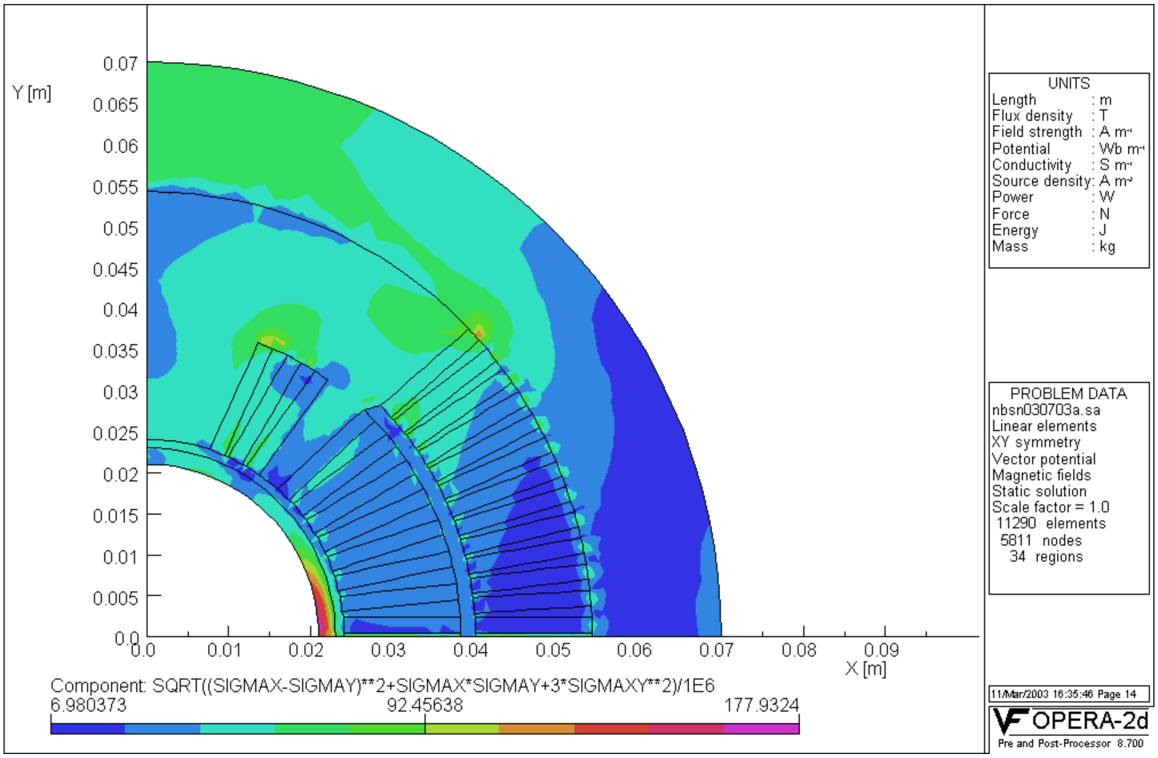

Fig. 13. Stress distribution in MPa at 10 T and 4.2 K

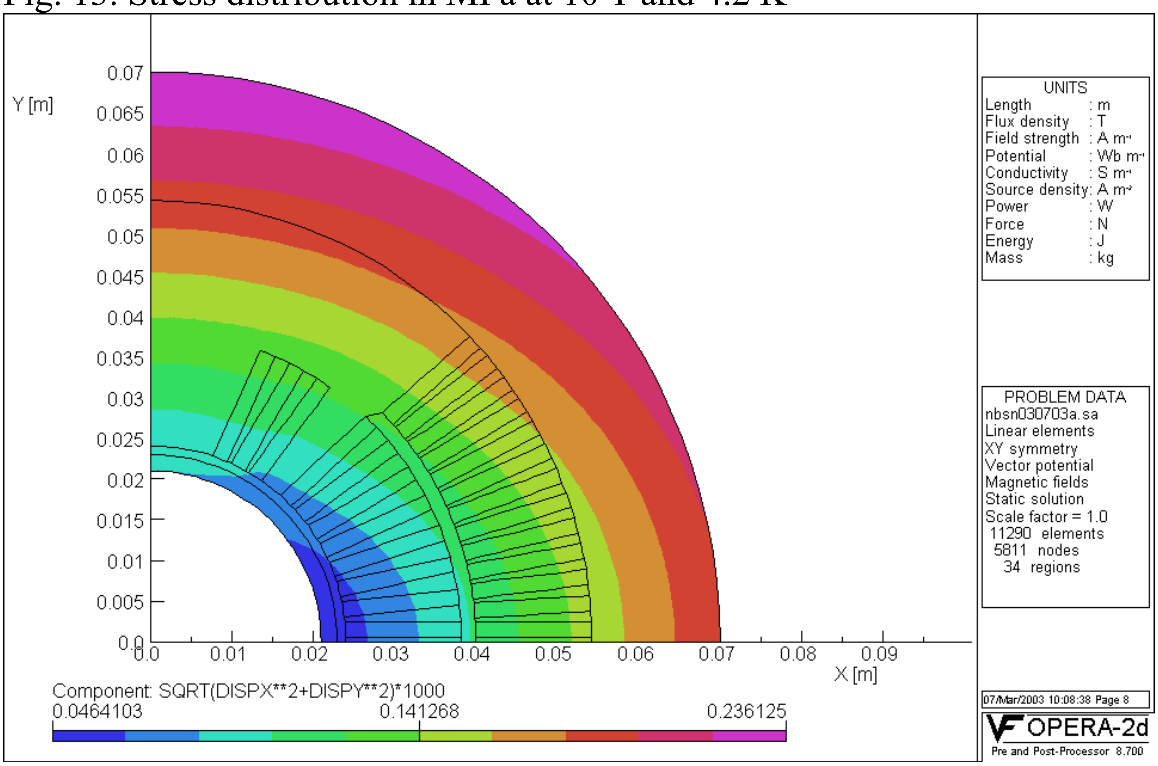

Fig. 14. Displacement distribution in mm at 10 T and 4.2 K

Appendix B

Technological Model

The model should prove a technological process of winding in conduit technology. Following issues should be investigated:

- epoxy impregnation under the pressure;
- epoxy and whole winding mold shrinkage effect;
- possibilities to keep winding prestress during and after curing;
- possibility to provide effective winding prestress after cooling down;
- epoxy pressurizing technique and devices;
- splitted volume for winding impregnation and additional prestress;
- low melt temperature alloy for additional prestress.

This model ~0.3 m long should have (see. Fig.15):
- inner SS tube;
- outer thick collar tube made from SS or combined with Al for extra prestress during cooling down;
- thin SS tube just with 0.5 mm clearance relatively outer tube;
- the winding space should be filled in with SC cable pieces;
- two inlets and two outlets for the winding and bladder type volumes;
- end plates should be welded to all these tubes with vacuum tight welding process;
- inlets and outlets should have plugs capable to resist high pressure.
- pressurizing devices should be connected to the inlets.

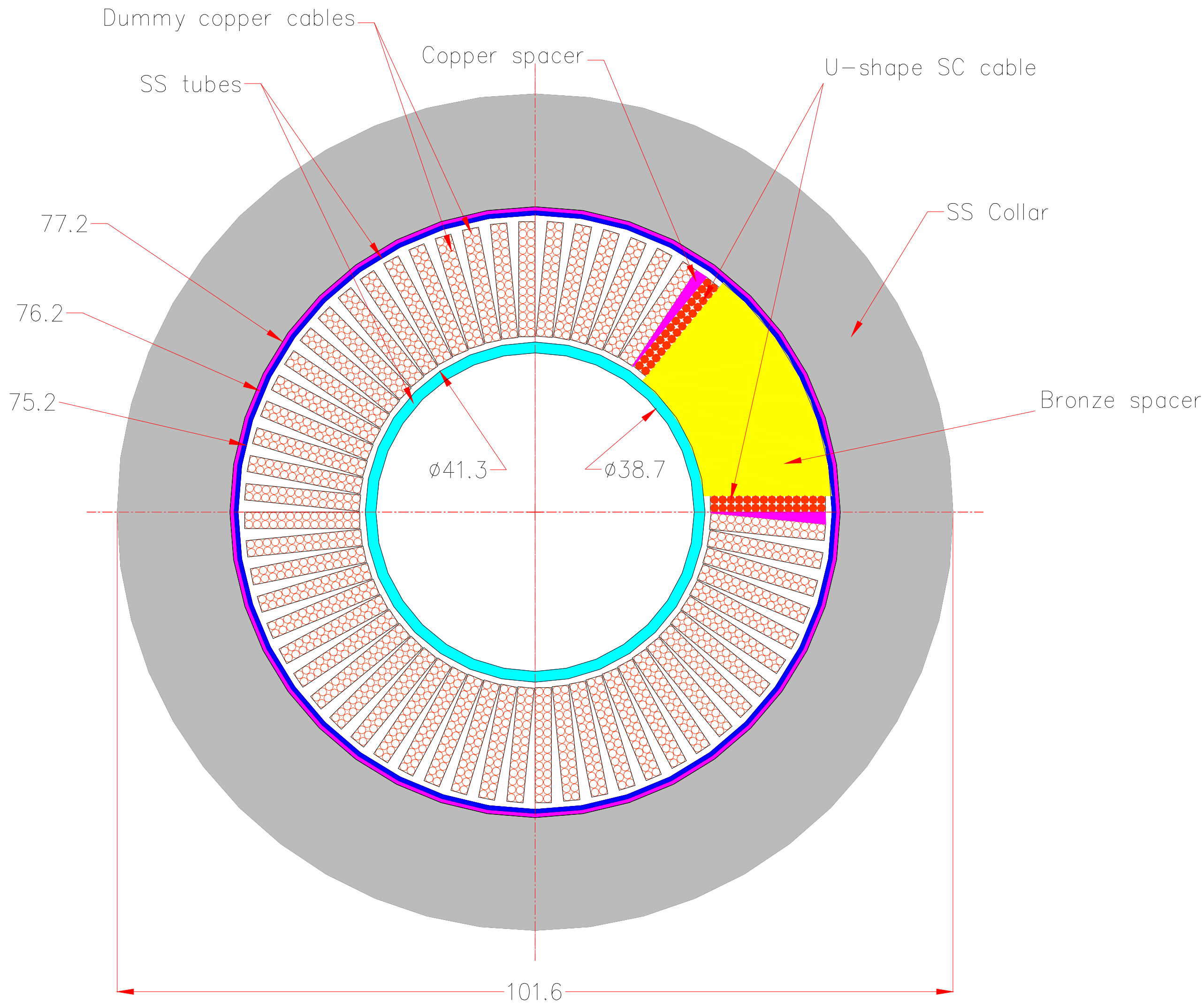

Fig. 15 Model cross-section

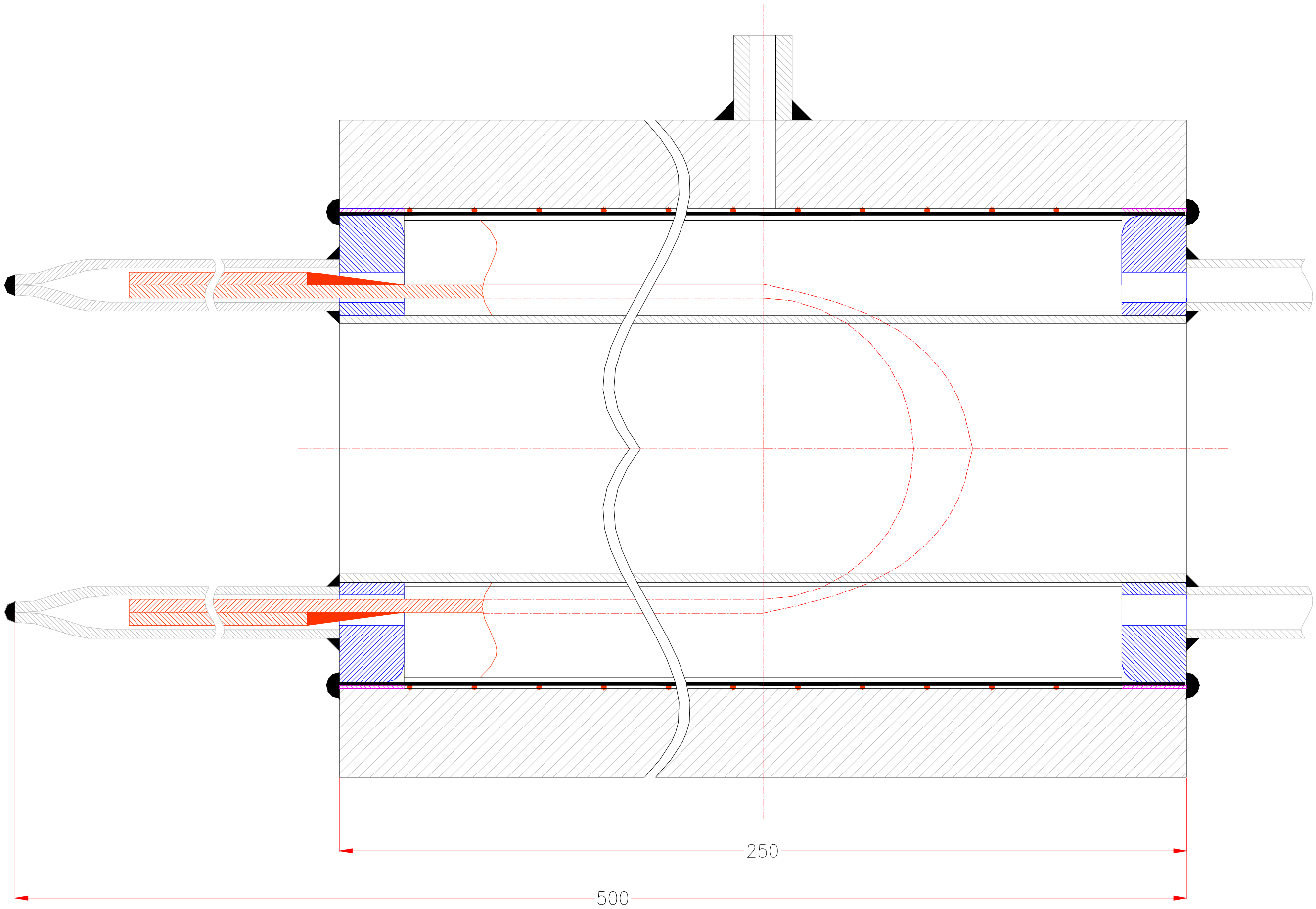

Fig. 16 Model longitudinal cross-section